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**The Future of Space Systems—  
The Challenge of Standards and  
Interoperability**

J. Morrison, Falcon Air Force Station,  
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THE FUTURE OF SPACE SYSTEMS --  
THE CHALLENGE OF  
STANDARDS AND INTEROPERABILITY

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John S. Morrison  
Lieutenant Colonel, USAF  
Director, Interoperability

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National Test Bed Joint Program Office  
Falcon AFB, CO 80912-5000

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SECTION I

THE INTEROPERABILITY IMPERATIVE

Developmental planning for the military use of space needs to be underpinned by a comprehensive interoperability program. Such a program is needed now to harness rapid technological change and meet future defense objectives in a cost-effective way. The program should be joint in nature, and broad enough to encompass the needs of multiple Services, Agencies and Departments. The National Test Bed can serve as its starting point.

Scope of the Problem. National security increasingly depends on the development and use of complex, interconnected systems which cooperate to a high degree to support multiple missions. This trend has been evident in tactical systems for many years and is becoming increasingly important for space systems. The notion that we can "grow" command, control, communications and intelligence (C3I) with each individual space system was appropriate when those systems were designed to meet limited objectives. The Strategic Defense Initiative and future operational concepts implied by the National Aerospace Plane and hypersonic boost-glide vehicle compel a major re-thinking of the approach to developing system requirements and maintaining associated space system interfaces. A much more comprehensive and systematic approach to obtaining C3I mission requirements and interoperability is needed to assure communication and data access across families of systems developed by a range of organizations, and supporting complementary but dissimilar missions across the spectrum of conflict. As the number of interface opportunities for military space systems grows, and as the systems themselves become more complex, it will become difficult to directly test their performance over the entire range of intended operation. Simulation will become an increasingly important tool, and interface specifications will be critical to achieving a desired level of performance and interoperability.

Interoperability among space systems will help improve capability, reduce costs, and provide a clear path for technology insertion. Just as Reduced Instruction Set Computers run faster by reducing the variety of intrinsic operations, parsing engines which generate and interpret messages can be made simple, efficient, and "standard" by adopting interface design standards which incorporate a minimum number of rules, message types and data codes. Simplified, standard interfaces will be easier to manage and will allow new systems, capable of cooperating with other systems, to be inserted quickly to perform new missions.

Interoperability, however, will not be without risks and challenges which are programmatic, fiscal, and technical in nature. A successful

interoperability program must have:

- ° Clear leadership, lines of authority, and designated advocates.
- ° Continued funding and direction.
- ° A process for developing and maintaining design goals and technical standards.
- ° A process for certifying that systems comply with interfaces, and an associated process for arbitrating disputes over interface compliance.
- ° A process for systematically determining how proposed changes to interface standards will impact on systems.

Interoperability programs are not new in DoD. The Congressionally-mandated program of Joint Task Force interoperability provides an excellent model. We do not need to reinvent the process, but only apply lessons learned. One such lesson is the need for cooperation among Services and Agencies.

The Need for a Joint Approach. Interoperability is inherently a joint process, and needs to be managed by a joint program. Standards cannot be determined by a single Service or Agency since they impact on the cost, schedule, and evolutionary potential of programs belonging to multiple Services and Agencies. Moreover, serious interoperability programs require full-time management and extensive coordination efforts by teams of technically-oriented people. Since interoperability benefits a range of users, it is appropriate that participating Services and Agencies each contribute technical manpower to the efforts. Standards, then, must be developed and maintained through broad participation and a consensus process. Once implemented, standards must be strictly enforced. This does not mean that standards cannot change or evolve; it means they cannot be modified unilaterally by a program, without regard to the potential impact on other cooperating systems. The proper focus for an interoperability program is on definitions, messages, and procedures.

Standard Messages. Interoperable messages are central to interface design standards. They provide a context for and give meaning to transmitted data. Messages can be character-, voice-, or bit-oriented, and their structure and content can be completely specified by a formal design language. (Ada Process Description Language is one example.) Rules for message transmission can also be formally specified, and channels of communications over which the messages flow can be rigorously defined. The goal of an interoperability program should be to get the right messages to the right systems (people or machines), at the right time, over the right channels, using the right procedures.

Standard Tools and Metrics. An interoperability program must be supported by standard tools and metrics, which include:

- ° Systems, procedures, and criteria for evaluating interoperability standards and certifying compliance.
- ° A central interoperability database containing existing and developmental standards.
- ° Another data base containing interoperability test plans, procedures, raw data, and evaluated results.
- ° A status-tracking system for proposed interface changes.

Many of the tools needed to support a space interoperability program will soon be in place as part of the National Test Bed (NTB) program, which will link major SDI research centers in a nation-

wide simulation network focused on strategic defense. This fact suggests a cost-effective interoperability approach.

## SECTION II

### APPROACH

Build a Limited Initial Program Based on Existing Assets and Organizations. SDI is a challenging subset of the space systems interoperability problem. A larger, more encompassing program could easily grow from this seed. The National Test Bed Joint Program Office has the charter, organization, and a growing set of tools to address SDI interoperability. When developed, the capability will leverage the assets of test ranges, laboratories, and research centers to focus on the technical feasibility of SDI. It will use simulations to assess the performance of interacting systems over a broad range of operational environments and scenarios. A common simulation framework will also be developed to allow engineering models of SDI elements to be evaluated within the context of the end-to-end, layered Strategic Defense System. The NTB must, of necessity, evolve in partnership with a family of participating organizations oriented toward the practical, military use of space.

Document What Exists. The first step in establishing an interoperability program is to catalog the existing models, tools, interface specifications and operational framework. These configuration items represent a foundation on which new systems may be built. Users and operators of space systems will have a vital hand in this process.

Define, Test and Implement Standards. The next step is to propose a set of interoperability standards which meet the needs of systems now being planned or developed. The development of such standards will require community participation. Proposed standards will be tested and evaluated against models of the evolving systems, or against man-in-the-loop/hardware-in-the-loop experiments. Interface design standards which test successfully and are adopted should be incorporated into those systems whose design baselines can accommodate them. For those systems in production, a case-by-case determination should be made to decide if increased mission capability, measured against the cost of system modification, warrants a retrofit.

Define Future Extensions and Growth Paths. A space interoperability program must be future-oriented of necessity, and must develop growth paths for the evolution of more complex and capable systems. Determination of future operational requirements is critical to defining such growth paths. For this reason, Office of the Joint Chiefs of Staff (OJCS) involvement will be as important for the interoperability of space systems as it is for tactical systems.

Test and Evaluate Interoperability Standards in Parallel with SDI Simulations and Experiments. Using a philosophy of "build a little, test a little," we can start building into our test plans for SDI the evaluation of interface standards. Initially we may find a diverse set of interface approaches. By systematically analyzing these approaches, we expect to converge on the most promising solutions which offer the widest benefit.

A system life cycle analysis should be accomplished for interface design standards just

as with any other developing "system." Such analysis should include, but not necessarily be limited to, sensitivity analysis, stability analysis, compatibility analysis, utility analysis and state-of-the-art analysis.

Sensitivity analysis looks at important parameters of the interface design standard, and varies them in turn to determine the effect on end-to-end simulation model performance. Parameters which are shown to have little or no effect on the systems and subsystems could be treated as constants, and the model simplified accordingly. Those showing large sensitivities need to be examined in greater detail since these affect system performance the most.

Stability analysis tests the interface standards for any tendencies to produce instabilities under various operating conditions. These tests are especially important for large constellations of complex, interacting systems, where failure modes may be difficult to foresee.

Compatibility analysis evaluates the ability of systems to exchange information. System parameters and models should be examined to make certain that interface conditions and system constraints are not being violated. Ideally, this analysis should include an examination of interdependencies of system parameters on lower-level (Section IV) interface parameters.

Utility/interoperability analysis addresses the value of the interface standard. For example, the value of a message is related to its speed of transmission, syntactic correctness, information content, and information accuracy (measured against objective reality). The value of message "strings" (sequences of messages, triggered by interface operating procedures) could be determined by how well they comply with interface rules and satisfy information demands of cooperating systems.

State-of-the-art analysis determines how well technology can support new interface design requirements and indicates potential problem (risk) areas in technology, cost or time.

Interface design standards may also be analyzed in terms of the usual "ilities" (reliability, maintainability, availability, security, etc.), as in other systems.

### SECTION III

#### THE INTEROPERABILITY PROCESS

Interface Change Proposals. An interoperability program must establish procedures for controlling interface definitions. One such procedure is the Interface Change Proposal (ICP). An ICP may be submitted by any participating Government organization. The development of a new system or the desire to improve interface flexibility, performance or security could justify submission of an ICP. Such proposals would include a concise description of an interface "problem," analysis of the problem justifying a change to the interface, a description of the proposed modification, and an initial impact statement. The Interface Change Proposal would be submitted for review by all participating organizations to determine the ramifications of the change.

Technical Assessment. The purpose of a technical assessment is to consider Interface Change Proposals submitted by participating organizations. Based on technical review, and perhaps supported by test results, formal panel recommendations and an impact analysis are drawn

up, which may include minority views.

Programmatic Assessment. The purpose of programmatic assessment is to review analysis and recommendations based on the technical assessment, and vote on whether or not to implement Interface Change Proposals. Recommendations are forwarded to the interface authority.

Interface Authority. The Joint Interface Authority is the keeper of the standard, and is the "court of last resort" for minority opinions. He either directs implementation of the interface modification, or he does not.

### SECTION IV

#### PRODUCTS

##### Interoperability Concept in Perspective.

Interoperability is the ability of systems to work together to perform a mission. To be useful, this abstract concept must be embodied in interoperability products used for system design. Such products include an interface architecture, interface concept, interface operating procedures for passing messages, message formats, definition and specifications for communications links and networks. A wide variety of tasks need to be successfully accomplished prior to developing these interoperability products, however. For example, analyses are required to:

- ° Determine which systems must interact in the variety of military missions to be performed.
- ° Determine the types of information that may be exchanged among the groups of systems in support of their mission roles.
- ° Identify individual system communications capabilities sufficient for establishing interface links with other participating systems.
- ° Determine the message loading and timeliness requirements for each system. This is necessary to ensure that the types of communications, in their deployment configuration, are suitable for the expected types of use.
- ° Develop an interoperability philosophy that will be flexible enough to permit changes in system roles and capabilities without imposing excessive cost penalties (on systems that have been previously developed) or reducing overall system effectiveness.

One useful frame of reference for considering interoperability is the International Standards Organization (ISO) Open System Interconnect model. This model defines seven architectural layers for interactive networks.

- ° Layer 1 -- Physical control
- ° Layer 2 -- Link control
- ° Layer 3 -- Network control
- ° Layer 4 -- Transport end-to-end control
- ° Layer 5 -- Session control
- ° Layer 6 -- Presentation control
- ° Layer 7 -- Process control (Applications)

In programs such as JINTACCS and TACS/TADS, interoperability testing typically begins with compatibility testing and proceeds to an evaluation of the utility of information and procedures. Following successful "laboratory" testing, the interfaces are "field tested." Systems are termed 'compatible' if they can 'talk' to one another (exchange data). In terms of the ISO model, this capability corresponds to layers 1-4. Interopera-

bility, which encompasses compatibility, is defined as the ability to use the communicated data. Thus, interoperability includes ISO layers 1-7.

The development of interoperability standards can be made manageable by decomposing the problem into smaller, logically consistent, and testable mission segments. For example, the JINTACCS program, which deals with interoperability within the Joint Task Force, initially defined the segments as Intelligence, Air Operations, Operations Control, Maritime, and Fire Support. A program for interoperable space systems might use a different mission-oriented break-down. One possible scheme follows, based in part on the Functional Decomposition developed by the SDI BM/C3 Working Group for Standards (Sept, 1986):

- ° Launch, Maneuver, Rendezvous, Docking and Recovery
- ° Health and Maintenance
- ° Command and Control
- ° Battle Management
- ° Fire/Weapon Control
- ° Surveillance
- ° Communications
- ° Computing and Simulation
- ° Experiments
- ° Exercise Control

#### Layered, Evolutionary Interface Architecture.

Space missions involving multiple Services and Agencies will ideally have architect-engineers responsible for developing and maintaining architectural configurations and associated interfaces which meet the mission goals. Interface architectures should be layered for the following reasons:

- ° Layering isolates mission functionality from the effects of system changes. For example, the upgrade of a communications link need not require a change in battle management applications program if the messages which drive those programs are not changed.

- ° Modularization by means of layering simplifies the overall design.

- ° Different layers can be assigned to different design teams and different standards committees.

- ° The relationship between the different control functions can be better understood when they are split into layers. This is especially true of control actions which occur sequentially in time from layer to layer.

- ° Common lower level services may be shared by different higher level users.

- ° Functions, especially at lower layers, may be removed from software and built into hardware or microcode.

- ° 'Plug-compatible' connections are easier to define.

There are a few disadvantages to layered architectures. These include the following:

- ° The total overhead is somewhat higher.
- ° The communicating machines may have to use certain functions which they could do without.
- ° To make each layer useable by itself, there is some small duplication of function between the layers.
- ° As technology changes (e.g., as cryptography and compaction chips become available,

or as the functions can be built onto HDLC chips) the functions may not be in the most cost-effective layer.

In general, the advantages of layered architectures are great, and the disadvantages are slight. A layered architecture can serve as the basis for evolutionary change, and defines the purpose and structure of system interfaces.

Technical Interface Concept. The Technical Interface Concept (TIC) documents interface requirements from a "user system" point of view, specifying interface opportunities among systems, and the type of information that must be exchanged. From this compilation in the TIC, an initial assessment can be made by the development planner as to which systems or activities will be impacted by the introduction of a new system. The needed categories of information for the proposed system may be determined in relation to operational requirements.

Technical Interface Operating Procedures (TIOP). Such procedures represent a comprehensive description of rules for sending and receiving messages. They describe the conditions which "trigger" a message transmission, the rules for determining addressees, and rules for selecting transmission channels and precedence. The application of such rules in message-driven systems produces time-ordered message "strings," in which messages spawn other messages. The validity of an observed message string can be evaluated by comparing it against the TIOP.

Technical Interface Design Plan. The TIDP catalogs the interoperable message and defines their structure. Standard message formats specify the organization and arrangement of the data fields in messages including address, control, and other system requirements, as well as the necessary information itself. The utility of the message format (which is distinct from the utility of the information content) is partially determined by how well the message conveys critical information, if and when such information is available.

Message formats may be either fixed or variable. Initial attempts at automated information exchange have involved the use of fixed format binary coded messages, such as the Tactical Automated Digital Information Links (TADILs). Optimal use of this technique is only achieved when applied to specific applications using well-defined and relatively unchanging messages.

One certainty in the evolution of C3I systems is that message modification will be an ongoing process. In addition, as the number of data links employing different basic message lengths (number of bits per frame) increases, it becomes increasingly difficult to define a common set of messages that can be exchanged (to provide interoperability) among a group of systems using a variety of these links. In summary, fixed format messages are limited in their ability to provide interoperability among C3I systems.

Generalized data transfer mechanisms using variable-format structured messages avoid the limitations of fixed formatting, and can treat fixed-format messages as a special case of a more generalized interface "language." A generalized data transfer mechanism can be thought of as providing a buffer between a message processor's application software and its digital data link protocol software (or firmware or hardware). A transmitted message (received from an applications program) would be translated from its system-unique representation to a normalized bit or byte

stream identical in all implementations of the same message. This stream of data would then be passed on to whatever mechanisms are responsible for encryption and adding data link protocols; following transmission, the process would then be reversed at the point of message receipt. In this way, interoperability is achieved because of the agreement in the appearance of the bit or byte stream; digital data link transparency is achieved because all such processing is carried on locally within a stream prior to creating the normalized data stream. Generalized data transfer also solves the problem of data base incompatibility by using interoperable messages as a common query language. The rules used to define the translation from local message forms to the common data stream representation can be described by a formal process description language. Such a language could describe character-oriented messages. In addition, language features could be added to accommodate the inevitable changes in message types and contents that are the result of an evolving C3I architecture.

Message Element Dictionary. An exhaustive catalog describing the format of fields contained in messages, and specifying the range and meaning of data item codes which can populate each field. The fields and their associated codes represent the smallest units of information meaningful to the mission. They are the lexical "atoms" which may be arranged and aggregated within messages, and their exact form and meaning must be standard across all cooperating systems.

Table of Data Item Codes. An exhaustive list of approved data item codes which can populate message fields.

Table of Algorithms and Equations. Standard algorithms and equations used to compute mission-related or communications-related information used by more than one system.

Table of Physical and Mathematical Constants. Authoritative List of physical and mathematical constants, to be used by all cooperating space systems.

Communications Channels Specifications. The communications channel specifications include functional details of the physical, link, network, and transport layers; channel capacity; expected bit error rates; and characterization of link, network and transport delays.

Interoperability Master Plan. Time-phased plan for approving, introducing, and upgrading interface design standards. The plan should specify the systems which will require the standards, and the organizations responsible for maintaining them.

The interoperability process must generate interoperability products within the context of a management structure. The next section suggests an organizational approach which encompasses all participating organizations, and provides a bridge between operational and developmental planning.

## SECTION V

### ORGANIZING FOR INTEROPERABILITY

The Tactical Interoperability Paradigm. The program for achieving Joint Interoperability Tactical Command and Control Systems gives the operational community responsibility for developing and coordinating requirements. Within the Air Force, Tactical Air Command is the single coordinating authority for interoperability requirements and standards, and executes a Program Management

Directive which provides direction and funding. ESD manages RDT&E funding for the program, and provides MITRE support. Other participating Services and Agencies have adopted a similar operationally-oriented approach. Each Service/Agency coordinating authority has one vote in a joint forum which recommends interface design standards to a joint interface authority. The joint interface authority oversees both a joint program office which acts as architect-engineer for interface standards, and a joint test activity responsible for verifying the interface design by conducting tests within a distributed joint testbed. When the joint interface authority determines that interface design standards have been verified through laboratory testing, the standards are turned over to a Unified Command for field testing and implementation. Once approved for implementation, standards are incorporated into JCS publications.

The organizational structure and relationships supporting tactical interoperability accommodate institutional and legal constraints on research and development while meeting the needs of the tactical forces. Leadership by the operational community in requirements development ensures that emerging interoperability standards are responsive to current and future mission concepts. Product division management of RDT&E funding and FCRC assets complies with Service policy. Joint program office management of architecture-engineering activities and testbed operation places responsibility for technical development within proper R&D channels, and assures a fair representation of Service/Agency views. Unified Command testing of the standards under field conditions ensures that they are workable, and incorporation of standards into JCS publications ensures compliance by system developers.

Organizing for Space Interoperability. The same institutional sensitivities which apply to developing interoperable standards for tactical systems also apply to space systems. Each participating Service/Agency should have a single, operationally-oriented focal point for coordinating interoperability requirements. Air Force Space Command would be a logical choice as the Air Force focal point. The National Test Bed is the logical place to conduct laboratory testing of interface design standards. The SDIO, because it is an OSD organization with broad responsibility for developing and integrating a variety of space-related systems, is the logical choice as the joint interface authority. U.S. Space Command should assume responsibility for field testing and eventual implementation of standards.

Interface design standards for a Strategic Defense System will be developed by the SDIO and tested in the National Test Bed even if no broader interoperability program is created. However, in this limited subset of the space interoperability problem there is a need for a systematic process which coordinates and prioritizes operational requirements and funnels them into the technical design of interfaces. Establishing a space interoperability office within Air Force Space Command will create such a process for the Air Force, and could prompt other Services and Agencies to follow suite.



## SECTION VI

### RECOMMENDATIONS

#### ° Endorse:

- Space systems interoperability program
- Suggested interoperability approach
- Need for well-defined products, process

#### RATIONALE:

- Gain additional leverage from future space applications
- Support planned evolution of complementary space capabilities.
- Improve mission effectiveness
- Support rapid technology insertion
- Lower system costs
- Provide visibility into the effects of change

#### ° Establish formal Air Force Interoperability Program

- Provide funding, direction, responsibility
- Air Force Space Command should be Service coordinating authority
- Feed requirements for interface design standards into SDI BM/C3 program for evaluation in NTB

#### RATIONALE:

- Creates formal, recognized mechanism for establishing and prioritizing Air Force interoperability requirements
- Spurs other Services to adopt similar programs
- Builds on existing SDI infrastructure

#### ° Obtain top-level management agreements needed for broad-based program

- Principals: OSD, OJCS, NASA, Army, Navy, DIA, NSA, DARPA
- Observers: NBS, DOE, NATO

#### RATIONALE:

- Creates formal mechanism for establishing and prioritizing National interoperability requirements.

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